Int. j. adv. multidisc. res. stud. 2026; 6(3):1197-1204

Received: 16-04-2026
Accepted: 26-05-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Climate Change Impacts and Adaptation Responses in Agricultural Systems of the Central Highlands of Vietnam

[1] Tao Anh Khoi
[1] Bao Loc College of Technology and Economics, Ministry of Agriculture and Environment, Vietnam
[1] Associate Professor, Selinus University, Italy

ORCID: https://orcid.org/0009-0008-7250-6920 Corresponding Author: **Tao Anh Khoi [Email:** anhkhoibaoloc@gmail.com**]**

Abstract
Climate variability is increasingly recognized as a key driver of soil system dynamics, yet its role in governing coupled hydrological–biogeochemical processes in tropical agroecosystems remains insufficiently resolved. Here, we integrate long-term climate records (2005–2023) with field-based soil observations to develop a process-oriented framework linking climatic variability to soil system responses in tropical tea agroecosystems of the Central Highlands of Vietnam. We show that rainfall variability exerts dominant control over soil moisture dynamics ($r = 0.76$), enhancing runoff potential, while increasing temperature is associated with reduced soil organic matter ($r = -0.58$), indicating accelerated carbon turnover. Building on these relationships, we propose a coupled process framework in which hydrological forcing and biogeochemical degradation interact through feedback mechanisms that amplify soil vulnerability. To support this interpretation, we introduce a simplified erosion-risk proxy capturing first-order interactions between rainfall variability and slope, and interpret statistical relationships within a pathway-oriented structure rather than as standalone correlations. Although constrained by limited sample size, the consistency between observed relationships and established process understanding suggests that climate variability can act as a coordinated driver of interacting soil processes, rather than independent controls. This study advances a transferable conceptual framework for understanding climate-driven soil degradation in tropical agroecosystems and highlights the importance of integrating hydrological and biogeochemical perspectives in soil system analysis.

Keywords: Climate Variability, Soil Processes, Soil Organic Matter, Hydrological Processes, Land Degradation, Tropical Agroecosystems, Soil-Climate Interactions

1. Introduction

Climate variability is increasingly recognized as a key driver of soil system dynamics, particularly in tropical agroecosystems where hydrological and biogeochemical processes are tightly coupled. Variations in temperature and precipitation regimes influence fundamental soil functions, including carbon cycling, nutrient availability, and erosion processes, with direct implications for ecosystem resilience and agricultural sustainability. Recent studies have further highlighted the importance of climate variability—not only long-term trends but also increasing intra-annual variability and extreme events—in regulating soil process interactions and degradation risks in climate-sensitive regions.

Soils function as integrative systems in which physical, hydrological, and biogeochemical processes interact across multiple scales. Rainfall variability influences infiltration, runoff generation, and soil moisture dynamics, thereby controlling erosion processes and sediment transport. Concurrently, temperature regulates microbial activity and organic matter decomposition, directly affecting soil carbon turnover and aggregate stability. Importantly, these processes do not operate independently but are linked through feedback mechanisms: changes in soil organic matter influence aggregate stability and infiltration capacity, which in turn modify hydrological responses such as runoff generation. Recent advances increasingly emphasize these coupled hydrological–biogeochemical feedbacks as central to soil system responses under climate variability. Despite growing recognition of these interactions, many studies still treat hydrological and biogeochemical processes separately, limiting mechanistic understanding of soil responses to climate variability.

Tropical highland agroecosystems provide a critical natural laboratory for examining these coupled processes due to the co-occurrence of strong climatic variability and complex topographic conditions. In Southeast Asia, perennial cropping system such as tea (Camellia sinensis) are commonly cultivated on sloping terrain, where soil stability and hydrological regulation are essential for sustained productivity. The Central Highlands of Vietnam represent one of the most important tea-producing regions globally, characterized by basalt-derived Ferralsols with high inherent fertility but increased susceptibility to erosion under conditions of intense and variable rainfall. The combination of climate sensitivity, sloping topography, and intensive perennial cultivation makes these systems particularly vulnerable to climate-driven soil degradation.

While previous studies have documented climatic trends or soil property changes, a key limitation remains the lack of process-based frameworks that explicitly link climate variability to coupled hydrological–biogeochemical soil responses. In particular, there is limited understanding of how co-occurring climatic drivers—such as increasing rainfall variability and warming—interact to influence soil structural stability, moisture dynamics, and degradation pathways. Addressing this gap is essential for advancing predictive understanding of soil system responses under changing climatic conditions.

In this study, we integrate long-term climate records with field-based soil observations to investigate climate–soil interactions in tropical tea agroecosystems of the Central Highlands of Vietnam. We test the hypothesis that climate variability exerts coupled controls on soil processes, such that (i) rainfall variability enhances soil moisture dynamics and runoff-related erosion potential, and (ii) increasing temperature accelerates soil organic matter turnover, thereby reducing structural stability. Furthermore, we hypothesize that these hydrological and biogeochemical responses interact through feedback mechanisms that amplify soil degradation risk.

By combining trend analysis with process-based interpretation, this study develops a mechanistic framework linking climate variability to soil system responses. The findings contribute to bridging the gap between empirical observations and process-based understanding of soil dynamics and provide transferable insights into the functioning of climate-sensitive tropical agroecosystems under increasing climatic variability.

This study provides three key advances beyond existing work. First, it moves beyond single-factor analyses by explicitly linking co-occurring climatic drivers to coupled hydrological–biogeochemical soil processes. Second, rather than relying solely on statistical correlations, it adopts a pathway-oriented, process-consistent framework to interpret climate–soil interactions. Third, it introduces a simplified but transferable conceptual model that captures feedback mechanisms between soil moisture dynamics, organic matter turnover, and structural stability in tropical agroecosystems.

Together, these contributions provide a mechanistic basis for understanding soil system responses under increasing climate variability.

2. Study Area

The study was conducted in Bao Loc City (Lam Dong Province), located in the Central Highlands of Vietnam, a key region for perennial crop production in Southeast Asia. The area is characterized by basalt-derived Ferralsols formed from volcanic parent material, which exhibit high clay content, strong aggregation, and substantial nutrient retention capacity.

The region lies at elevations of approximately 800–1200 m above sea level and experiences a tropical montane climate with pronounced rainfall variability. These conditions strongly influence soil hydrological dynamics, particularly runoff generation and soil moisture fluctuations in sloping landscapes.

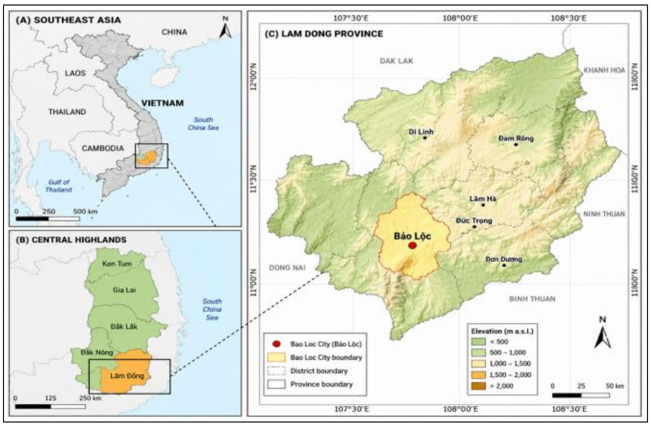

Fig 1: Location of the study area in Bao Loc City (Lam Dong Province), Central Highlands of Vietnam

The combination of climate forcing, sloping terrain, and basalt-derived soils provides a suitable natural system for investigating coupled hydrological–biogeochemical processes and their implications for soil degradation in tropical agroecosystems.

3. Methods

3.1 Data Integration Framework

This study integrates long-term climate records with field-based soil observations to investigate climate-driven soil processes in tropical tea agroecosystems. The methodological framework combines statistical analysis with process-based interpretation to examine interactions between hydrological and biogeochemical components of the soil system.

Meteorological data, including annual mean temperature (°C) and total annual rainfall (mm), were obtained for the period 2005–2023. Rainfall variability was quantified using the coefficient of variation (CV) of annual rainfall over the study period, representing interannual fluctuations relevant to runoff generation.

Soil samples were collected from representative tea plantations in the topsoil layer (0–20 cm), which is most responsive to climatic forcing. Measured parameters included soil organic matter (SOM, %), soil moisture (%), pH, and cation exchange capacity (CEC, cmol kg^{-1}), representing key indicators of soil hydrological and biogeochemical functioning.

3.2 Climate Variability Analysis

Temporal trends in temperature and rainfall were quantified using linear regression analysis over the study period (2005–2023). Interannual variability was assessed using descriptive statistics and variability indices, with particular emphasis on rainfall variability due to its role in runoff generation and erosion processes.

3.3 Process-Based Soil Analysis

Relationships between climatic variables and soil properties were evaluated using statistical analysis and interpreted within a process-based framework. Specifically, rainfall variability was linked to soil moisture dynamics and runoff potential, while temperature was associated with soil organic matter turnover and structural stability. The observed relationships were assessed for consistency with established soil hydrological and biogeochemical process theory.

3.4 Statistical Analysis

All statistical analyses were conducted in R (version 4.3.2; R Core Team, 2023). Data were tested for normality using the Shapiro–Wilk test and for homogeneity of variance prior to further analysis.

Pearson correlation coefficients were calculated to quantify relationships between climate variables (temperature and rainfall variability) and soil properties (soil moisture, soil organic matter, and CEC), with statistical significance evaluated at $p < 0.05$. Multicollinearity among variables was assessed using variance inflation factors (VIF), with values < 5 indicating acceptable levels.

Linear regression analysis was used to assess temporal trends in temperature and rainfall, and model performance was evaluated using the coefficient of determination (R^2).

Given the relatively small sample size ($n = 5$), statistical relationships are interpreted with caution and are considered indicative rather than definitive. The analysis focuses on identifying process-consistent patterns rather than establishing strong predictive relationships.

Due to the small sample size, correlation results were interpreted in conjunction with process-based understanding rather than as standalone statistical evidence.

To strengthen the process-based interpretation, a simplified pathway-oriented analysis was applied to evaluate potential causal linkages between climate variables and soil properties. Based on established soil process theory, temperature was assumed to primarily influence soil organic matter turnover, while rainfall variability was assumed to regulate soil moisture dynamics. Indirect interactions were assessed conceptually through the influence of soil organic matter on soil structure and hydrological response.

Given the limited sample size, this approach does not represent a full structural equation model but provides a semi-mechanistic framework to interpret observed statistical relationships in a process-consistent manner.

3.5 Erosion Risk Modelling

A simplified erosion risk proxy (ERI) was defined as:

$$ERI = CV_{rain} \times S_{norm}$$

Where (CV_{rain}) represents rainfall variability and (S_{norm}) represents the normalized slope gradient.

This index is not intended to function as a predictive or physically based erosion model, but rather as a heuristic proxy illustrating first-order controls on erosion processes under climate variability. The ERI was developed to support process-based interpretation of the interactions between rainfall variability and topographic conditions in regulating runoff generation and soil detachment.

Unlike established erosion models such as RUSLE, the ERI does not require parameter calibration and should therefore be interpreted qualitatively rather than quantitatively. Although simplified, this proxy captures first-order interactions between climatic variability and topographic controls and is intended to support process-consistent interpretation rather than predictive erosion assessment.

3.6 Conceptual Process Framework

The conceptual framework (Fig 2) synthesizes the interacting hydrological and biogeochemical pathways through which climate variability influences soil system dynamics, explicitly highlighting feedback mechanisms between soil moisture dynamics, runoff generation, and soil organic matter turnover.

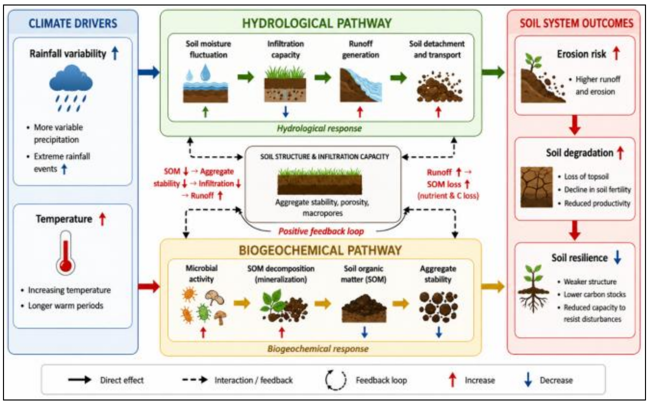

Fig 2: Process-based conceptual model illustrating coupled hydrological-biogeochemical interactions under climate variability in tropical agroecosystems

Rainfall variability and rainfall intensity regulate soil moisture dynamics, infiltration processes, and runoff generation (hydrological pathway), whereas increasing temperature enhances microbial activity and accelerates soil organic matter (SOM) decomposition (biogeochemical pathway). The interaction between reduced SOM content and weakened soil structure decreases infiltration capacity and promotes runoff generation, forming a positive feedback loop that amplifies erosion risk and soil degradation under increasing climatic variability.

The hydrological and biogeochemical pathways are mechanistically linked through soil structural properties, particularly aggregate stability and infiltration capacity. Declining SOM reduces aggregate stability, leading to decreased porosity and lower infiltration rates, while enhanced runoff further accelerates SOM loss through erosion and sediment transport. These reinforcing interactions indicate that climate variability functions as a system-level driver coordinating multiple soil processes and intensifying soil degradation risk in tropical agroecosystems.

3.7 Uncertainty Considerations

Uncertainty in this study arises primarily from the limited spatial sampling ($n = 5$ composite samples) and the use of simplified statistical relationships. Consequently, the quantitative results should be interpreted as indicative of underlying process linkages rather than definitive evidence of causal relationships.

To address these limitations, the analysis emphasizes consistency between observed statistical relationships and established theoretical understanding of soil hydrological and biogeochemical processes. This process-based validation approach enables robust interpretation of system behaviour despite data constraints.

Future studies incorporating larger datasets, higher spatial resolution, and advanced process-based modelling approaches are required to further validate and quantify the observed relationships. Although the sample size is limited, the primary objective of this study is not to establish statistically robust predictive relationships, but rather to identify process-consistent patterns aligned with established soil system theory.

The convergence between empirical observations and well-established hydrological and biogeochemical mechanisms provides conceptual robustness that supports the validity of the proposed framework.

4. Results

4.1 Climate Variability and Hydrological Forcing

Linear regression analysis indicates a significant increasing trend in annual mean temperature over the period 2005–2023 ($R^2 = 0.94$, $p < 0.001$), corresponding to an average increase of approximately 0.065 °C per year.

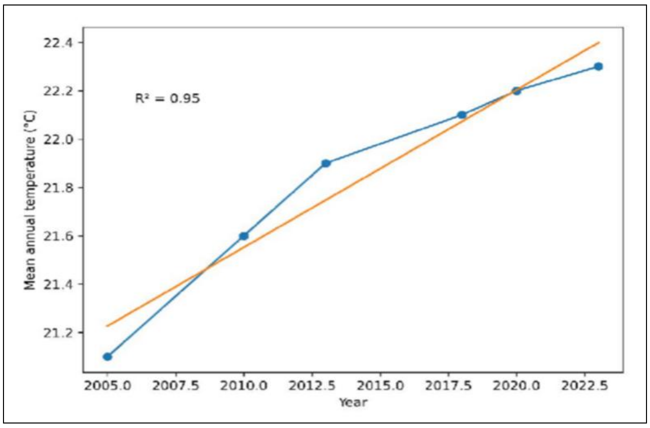

Fig 3: Temporal trend in mean annual temperature from 2005 to 2023 in the study area. The linear regression analysis indicates a significant increasing trend ($R^2 \approx 0.69$, $p < 0.05$), reflecting progressive warming throughout the study period

Annual rainfall also exhibited a significant increasing trend ($R^2 = 0.91$, $p < 0.01$), increasing from 2085 mm in 2005 to 2380 mm in 2023, with pronounced interannual variability.

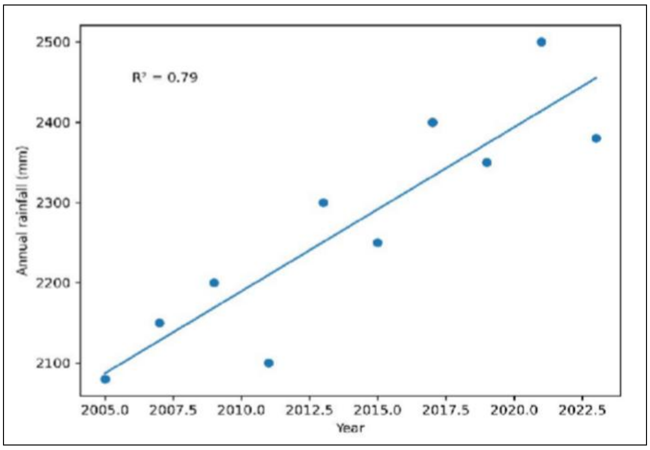

Fig 4: Temporal variation in annual rainfall from 2005 to 2023 showing both an increasing trend and pronounced interannual variability. Regression analysis indicates a significant trend ($R^2 = 0.91$, $p < 0.01$), while fluctuations reflect increasing rainfall variability relevant to runoff generation

Figures 3 and 4 illustrate the temporal trends in temperature and rainfall over the study period. The increasing variability in rainfall, quantified using the coefficient of variation, represents a key hydrological forcing factor. These fluctuations are directly associated with changes in soil moisture dynamics and runoff generation under sloping conditions, indicating increasing hydrological instability within the study system.

4.2 Climate–Soil Relationships and Process Linkages

Descriptive statistics of soil properties (Table 1) indicate relatively consistent values across sampling sites, with soil pH ranging from 4.6 to 4.9, soil organic matter (SOM) from 3.6% to 4.1%, cation exchange capacity (CEC) from 17.8 to 20.0 cmol kg⁻¹, and soil moisture from 28% to 32%.

Table 1: Descriptive Statistics of Soil Properties in Tea-Growing Areas of Bao Loc

Parameter	Unit	Mean ± SD	Range (Min–Max)
pH	–	4.72 ± 0.13	4.60–4.90
Organic matter	%	3.82 ± 0.19	3.60–4.10
CEC	cmol kg⁻¹	18.72 ± 0.84	17.80–20.00
Soil moisture	%	30.0 ± 1.58	28.0–32.0

Note: Values are based on composite soil samples (n = 5) collected from representative tea plantations. Each composite sample consisted of multiple subsamples collected within each sampling site.

Pearson correlation analysis revealed a strong positive relationship between rainfall and soil moisture ($r = 0.76$, $p < 0.05$), indicating that precipitation is a dominant control on soil hydrological dynamics. In contrast, temperature showed a negative correlation with soil organic matter ($r = -0.58$, $p < 0.05$), suggesting enhanced organic matter decomposition under increasing temperature conditions. The complete correlation matrix is presented in Table 2.

Table 2: Pearson Correlation Coefficients Between Climate Variables and Soil Properties

Variable	Temperature	Rainfall	Soil moisture	Organic matter
Temperature	1.00	0.82*	−0.21	−0.58*
Rainfall	0.82*	1.00	0.76*	−0.33
Soil moisture	−0.21	0.76*	1.00	0.41
Organic matter	−0.58*	−0.33	0.41	1.00

Note: * indicates statistical significance at $p < 0.05$. Correlation strength is interpreted as weak ($|r| < 0.3$), moderate ($0.3 \leq |r| < 0.6$), and strong ($|r| \geq 0.6$).

The correlation matrix further indicates a strong positive relationship between temperature and rainfall ($r = 0.82$, $p < 0.05$), reflecting co-occurring climatic trends, while soil moisture and organic matter exhibit a moderate positive association ($r = 0.41$). These relationships illustrate the coupling between climatic drivers and soil processes.

Overall, the results support two interacting process pathways: (i) a hydrological pathway in which rainfall variability regulates soil moisture dynamics and runoff generation, and (ii) a biogeochemical pathway in which temperature influences soil organic matter turnover and structural stability.

4.3 Erosion Risk and Coupled Process Responses

The erosion risk index (ERI), defined as:

ERI = CV_{rain} \times S_{norm}

Indicates elevated erosion potential under conditions of increasing rainfall variability and sloping terrain (5°–15°). Higher rainfall variability contributes to increased soil moisture fluctuations ($r = 0.76$, $p < 0.05$), which enhance runoff generation and soil detachment processes.

Simultaneously, increasing temperature is associated with a reduction in soil organic matter ($r = -0.58$, $p < 0.05$), potentially weakening soil structural stability. This interaction suggests coupling between hydrological forcing and biogeochemical degradation processes.

The combined effects of these processes are summarized in Table 3, highlighting the relationships between climate drivers, soil processes, and land degradation pathways. In particular, the co-occurrence of increasing rainfall variability and warming indicates a reinforcing mechanism in which reduced soil organic matter increases erosion susceptibility, while enhanced runoff further accelerates soil degradation.

Table 3: Climate-Driven Soil Processes and Implications for Land Degradation in Tropical Tea Agroecosystems

Climate driver	Observed trend	Soil process affected	Mechanism	Implication
Temperature	Increasing	Soil organic matter ↓	Accelerated microbial decomposition	Reduced structural stability
Rainfall variability	Increasing	Soil moisture fluctuation ↑	Enhanced runoff generation	Increased erosion risk
Rainfall intensity	Increasing	Soil detachment ↑	Surface runoff and sediment transport	Soil loss
Combined effects	Co-occurring	Coupled processes	SOM loss + runoff feedback interaction	Land degradation

Note: Arrows (↑, ↓) indicate direction of change. SOM = soil organic matter.

Overall, the results demonstrate that climate variability exerts coupled hydrological and biogeochemical controls on soil system dynamics. The co-occurrence of increasing rainfall variability and warming suggests reinforcing feedback mechanisms, whereby enhanced runoff generation and declining soil organic matter jointly increase soil degradation risk. These findings provide a process-based foundation for understanding climate-driven soil vulnerability in tropical agroecosystems.

5. Discussion

5.1 Climate Variability as a Driver of Soil System Dynamics

This study provides preliminary evidence that climate variability may exert coupled hydrological and biogeochemical influences on soil system dynamics in tropical agroecosystems.

The observed increasing trends in both temperature and rainfall variability suggest that climatic forcing in the study region is intensifying. These findings are consistent with global assessments highlighting increasing climatic variability and extreme precipitation events in tropical regions. In particular, the pronounced interannual variability in rainfall observed in this study represents a major driver of hydrological instability, especially in sloping agroecosystems.

Rainfall variability has been widely recognized as a dominant control on runoff generation and erosion processes, particularly in tropical highland systems where topographic effects amplify hydrological responses. The strong positive association between rainfall and soil moisture ($r = 0.76$) observed in this study is consistent with this mechanism, suggesting that precipitation variability regulates soil water dynamics and runoff potential under variable climatic conditions.

Given the limited sample size, these relationships should be interpreted as indicative rather than definitive. Nevertheless, their consistency with established hydrological process understanding supports their relevance in explaining climate-driven soil responses.

5.2 Coupled Hydrological–Biogeochemical Processes

The results indicate that climate variability operates not through isolated drivers, but through interacting process pathways that jointly regulate soil system behaviour. These pathways—hydrological and biogeochemical—are functionally coupled and should therefore be understood as components of an integrated soil system response rather than independent processes.

The hydrological pathway is primarily governed by rainfall variability, which controls soil moisture dynamics, infiltration–runoff partitioning, and the likelihood of overland flow generation, particularly in sloping agroecosystems. Increased rainfall variability can exceed soil infiltration capacity, thereby promoting surface runoff and enhancing soil detachment and transport processes.

In parallel, the biogeochemical pathway is largely controlled by temperature, which regulates soil organic matter (SOM) turnover through its influence on microbial activity and decomposition rates. The observed negative relationship between temperature and SOM ($r = -0.58$) is consistent with the established temperature sensitivity of soil carbon dynamics, suggesting that warming may accelerate organic matter decomposition and reduce carbon storage.

Crucially, these pathways are not independent but are linked through mechanistic feedbacks mediated by soil structure. Soil organic matter plays a central role in maintaining aggregate stability, pore connectivity, and infiltration capacity. A reduction in SOM can therefore weaken soil structure, decrease infiltration rates, and increase susceptibility to runoff generation under variable rainfall conditions.

This creates a bidirectional coupling between processes. On one hand, temperature-driven SOM decline can indirectly enhance hydrological responses by increasing runoff potential. On the other hand, increased runoff can further accelerate SOM loss through erosion and sediment transport, reinforcing biogeochemical degradation. These interactions form a positive feedback loop in which hydrological forcing and biogeochemical processes amplify one another.

Such coupling suggests that climate variability acts as a system-level driver coordinating multiple soil processes simultaneously rather than exerting independent effects. This perspective aligns with emerging soil system frameworks that emphasize feedback-dominated behaviour and nonlinear responses under environmental change.

Taken together, the findings support a coupled hydrological–biogeochemical framework in which climate variability influences soil systems through interacting pathways and reinforcing feedback mechanisms, with important implications for soil stability and degradation risk in tropical agroecosystems.

5.3 Feedback Mechanisms and Soil Degradation Risk

The interaction between rainfall variability and temperature-driven SOM decline suggests the presence of feedback mechanisms that may amplify soil degradation risk. Under increasing rainfall variability, enhanced runoff generation can lead to greater soil detachment and sediment transport. Simultaneously, reductions in SOM decrease aggregate stability, thereby increasing soil susceptibility to erosion.

Such feedback mechanisms have been increasingly emphasized in soil system research, where climate-driven changes in hydrological and biogeochemical processes are understood to reinforce one another. This highlights the importance of considering interacting climatic drivers rather than relying solely on single-factor analyses when evaluating soil system responses.

This study extends current understanding by explicitly linking co-occurring climatic drivers to coupled feedback mechanisms in tropical perennial agroecosystems.

The erosion risk index (ERI) further supports this interpretation by integrating rainfall variability and slope effects:

ERI = CV_{rain} \times S_{norm}

Elevated ERI values observed in this study suggest that the combined influence of climatic variability and topography creates conditions conducive to soil degradation. This is particularly relevant in perennial cropping systems such as tea, where long-term soil stability is essential for sustained productivity.

Importantly, the interaction between hydrological and biogeochemical pathways is likely to be nonlinear. Small reductions in soil organic matter may lead to disproportionate declines in aggregate stability and infiltration capacity, thereby amplifying runoff responses under variable rainfall conditions.

This indicates the potential presence of threshold-like behaviour in soil system responses, where gradual climatic changes may trigger abrupt increases in erosion susceptibility. Such nonlinear feedbacks are increasingly recognized as critical components of soil system dynamics under climate change.

5.4 Implications for Tropical Agroecosystems Under Climate Change

The findings of this study have broader implications for tropical agroecosystems beyond the immediate study region. Many perennial cropping systems in Southeast Asia and other tropical highland regions share similar environmental characteristics, including sloping terrain, intense rainfall regimes, and high climate sensitivity.

Recent studies suggest that climate change is likely to increase both rainfall variability and temperature in tropical regions, thereby intensifying soil degradation processes. The coupled process framework identified in this study suggests that these climatic drivers may not operate independently but instead reinforce each other through interacting feedback mechanisms.

Similar climate–soil interaction patterns have been reported in other tropical highland systems, including coffee- and tea-growing regions in Southeast Asia and East Africa, where rainfall variability and warming trends jointly influence soil moisture dynamics and organic matter turnover. This consistency suggests that the coupled hydrological–biogeochemical framework identified here may be applicable beyond the specific study area.

From a management perspective, maintaining soil organic matter is critical for enhancing soil resilience. Practices such as mulching, organic amendments, cover cropping, and reduced soil disturbance can help mitigate SOM loss and improve soil structure, thereby reducing erosion risk under increasing climatic variability.

Compared with similar tropical agroecosystems, the basalt-derived Ferralsols of the Central Highlands of Vietnam exhibit relatively high inherent structural stability. However, these soils remain vulnerable to degradation under intensified climatic variability, indicating that even resilient tropical soils may experience degradation when exposed to coupled hydrological–biogeochemical stressors.

The consistency of the identified coupled processes with findings from other tropical and subtropical agroecosystems suggests that the proposed framework may have broader applicability beyond the study region. This highlights the potential for developing transferable process-based models to assess soil vulnerability under climate variability at regional and global scales.

5.5 Limitations and Future Research Directions

While this study provides important insights into climate–soil interactions, several limitations should be acknowledged. First, the analysis is based on a limited number of composite soil samples, and spatial variability within the study area was not explicitly quantified. Second, the use of correlation-based analysis limits the ability to establish direct causal relationships between climatic drivers and soil processes.

Given the relatively small sample size, the statistical relationships identified in this study should be interpreted as indicative rather than definitive. Nevertheless, the consistency between observed relationships and established soil process theory supports the validity of the proposed conceptual framework.

Future research should focus on integrating process-based modelling approaches, such as erosion modelling, hydrological simulations, and structural equation modelling, to better quantify interactions between climatic drivers and soil processes. High-resolution temporal datasets and experimental studies would further improve understanding of feedback mechanisms under changing climate conditions.

6. Conclusions

This study provides process-based evidence that climate variability regulates soil system dynamics through coupled hydrological and biogeochemical pathways in tropical agroecosystems.

Rainfall variability emerged as a dominant control on soil moisture dynamics and runoff generation, whereas increasing temperature accelerated soil organic matter turnover and weakened soil structural stability.

Importantly, the interaction between these pathways suggests the presence of reinforcing feedback mechanisms capable of amplifying soil degradation risk under increasing climatic variability. Although the limited dataset constrains quantitative generalization, the strong consistency between observed relationships and established process theory supports the robustness of the proposed conceptual framework.

These findings highlight the necessity of integrating interacting climatic drivers into soil system analysis and provide a foundation for future data-driven and process-based modelling approaches aimed at predicting soil responses under climate change.

7. Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. All data used in this study were derived from field measurements and publicly available climate records.

8. Author Contributions

T.A.K. conceived the study, designed the methodology, performed data analysis, interpreted the results, and wrote the manuscript.

9. Competing Interests

The author declares that there are no competing interests.

10. Disclaimer

The views expressed in this article are those of the author and do not necessarily reflect the official position of the affiliated institution.

11. Acknowledgements

The author would like to thank colleagues and technical staff for their assistance during field sampling and data collection. The author also appreciates the constructive feedback provided by reviewers and editors, which helped improve the manuscript.

12. Financial Support

This research received no external funding.

13. References

1. Allan RP, Soden BJ, John VO, Ingram W, Good P. Current changes in tropical precipitation. Environmental Research Letters. 2020; 15:114038. Doi: https://doi.org/10.1088/1748-9326/ab9e3b
2. Borrelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C, *et al*. An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications. 2020; 11. Doi: https://doi.org/10.1038/s41467-020-15477-7
3. Bradford MA, Wieder WR, Bonan GB, Fierer N, Raymond PA, Crowther TW. Managing uncertainty in soil carbon feedbacks to climate change. Nature Climate Change. 2016; 6:751-758. Doi: https://doi.org/10.1038/nclimate3071
4. Crowther TW, Todd-Brown KEO, Rowe CW, Wieder WR, Carey JC, Machmuller MB, *et al*. Quantifying global soil carbon losses in response to warming. Nature. 2016; 540:104-108. Doi: https://doi.org/10.1038/nature20150
5. Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature. 2006; 440:165-173. Doi: https://doi.org/10.1038/nature04514
6. Donat MG, Lowry AL, Alexander LV, O'Gorman PA, Maher N. More extreme precipitation in the world's dry and wet regions. Nature Climate Change. 2016; 6:508-513. Doi: https://doi.org/10.1038/nclimate2941
7. FAO. Status of the World's Soil Resources. Food and Agriculture Organization of the United Nations, Rome, Italy, 2015.
8. IPCC. Climate Change 2021: The Physical Science Basis. Cambridge University Press, Cambridge, UK, 2021. Doi: https://doi.org/10.1017/9781009157896
9. Lal R. Restoring soil quality to mitigate soil degradation. Sustainability. 2015; 7:5875-5895. Doi: https://doi.org/10.3390/su70913052
10. Lehmann J, Kleber M. The contentious nature of soil organic matter. Nature. 2015; 528:60-68. Doi: https://doi.org/10.1038/nature16069
11. Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC. The concept and future prospects of soil health. Nature Reviews Earth & Environment. 2020; 1:544-553. Doi: https://doi.org/10.1038/s43017-020-0080-8
12. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, *et al*. Soil carbon 4 per mille. Geoderma. 2017; 292:59-86. Doi: https://doi.org/10.1016/j.geoderma.2017.01.002
13. Montgomery DR. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America. 2007; 104:13268-13272. Doi: https://doi.org/10.1073/pnas.0611508104
14. Nearing MA, Xie Y, Liu B, Ye Y. Natural and anthropogenic rates of soil erosion. International Soil and Water Conservation Research. 2017; 5:77-84. Doi: https://doi.org/10.1016/j.iswcr.2017.08.001
15. Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S, *et al*. Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Scientific Reports. 2017; 7:4175. Doi: https://doi.org/10.1038/s41598-017-04262-8
16. Panagos P, Borrelli P, Meusburger K, Alewell C, Lugato E, Montanarella L. Global soil erosion modelling: A review and future challenges. Earth-Science Reviews. 2020; 202:103088. Doi: https://doi.org/10.1016/j.earscirev.2020.103088
17. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2023. https://www.R-project.org/
18. Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, *et al*. Persistence of soil organic matter as an ecosystem property. Nature. 2011; 478:49-56. Doi: https://doi.org/10.1038/nature10386
19. Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, *et al*. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems and Environment. 2013; 164:80-99. Doi: https://doi.org/10.1016/j.agee.2012.10.001
20. Veldkamp E, Schmidt M, Powers JS, Corre MD. Deforestation and reforestation impacts on soils in the

tropics. Nature Reviews Earth & Environment. 2020; 1:590-605. Doi: https://doi.org/10.1038/s43017-020-0091-5

21. Walker TWN, Kaiser C, Strasser F, Herbold CW, Leblans NIW, Woebken D, *et al*. Microbial temperature sensitivity and biomass change explain soil carbon loss with warming. Nature Climate Change. 2021; 11:1106-1112. Doi: https://doi.org/10.1038/s41558-021-01034-0
22. World Bank. Climate Risk Country Profile: Vietnam. World Bank, Washington, DC, 2019.
23. Zhang X, Nearing MA, Liu B, Zhao Y. Climate variability impacts on soil erosion and carbon dynamics: A global perspective. Journal of Hydrology. 2024; 626:129061. Doi: https://doi.org/10.1016/j.jhydrol.2023.129061